High-Resolution Mesoscale Simulations of the 6-7 May 2000 Missouri Flash Flood: Impact of Model Initialization and Land Surface Treatment

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Abstract

High-resolution mesoscale model simulations of the 6-7 May 2000 Missouri flash flood event were performed to test the impact of model initialization and land surface treatment on timing, intensity, and location of extreme precipitation. In this flash flood event, a mesoscale convective system (MCS) produced over 340 mm of rain in roughly 9 hours in some locations. Two different types of model initialization were employed: 1) NCEP global reanalysis with 2.5-degree grid spacing and 12-hour temporal resolution, and 2) Eta reanalysis with 40-km grid spacing and 3-hour temporal resolution. In addition, two different land surface treatments were considered. A simple land scheme (SLAB) keeps soil moisture fixed at initial values throughout the simulation, while a more sophisticated land model (PLACE) allows for rainfall-soil moisture interactive feedback.

Simulations with high-resolution Eta model initialization show considerable improvement in the intensity of precipitation due to the presence in the initialization of a residual mesoscale convective vortex (MCV) from a previous MCS. Simulations with the PLACE land model show improved location of heavy precipitation. Since soil moisture can vary over time in the PLACE model, surface energy fluxes exhibit strong spatial gradients. These surface energy flux gradients help produce a strong low-level jet (LLJ) in the correct location. The LLJ then interacts with the cold outflow boundary of the MCS to produce new convective cells. The simulation with *both* high-resolution model initialization and time-varying soil moisture best reproduces the intensity and location of observed rainfall.

1. Introduction

Prediction of flash flood events, especially those caused by mesoscale convective systems, remains one of the most challenging problems in hydrometeorology. Numerical models generally underestimate total rainfall for extreme precipitation events, and often miss the timing and location of the event entirely. For example, average threat scores from the National Center for Environmental Prediction (NCEP) 32-km Eta model for 9 meso-high events with a threshold of 2 inches of rainfall were near zero (a threat score of 1.0 represents a perfect forecast) (Watson, 2000). Since flash flooding produces the most fatalities of any convective storm event (Doswell *et al.*, 1996), improvement of numerical models to capture extreme precipitation events is imperative. In this paper, we explore two approaches (model initialization and land surface treatment) that result in improved numerical simulation of a flash flood event in east-central Missouri on 6-7 May 2000.

A number of studies have explored the effect of horizontal grid resolution on the simulation of convective events (e.g., Weisman *et al.*, 1997; Bernardet *et al.*, 2000; Roebber and Eise, 2001; Belair and Mailhot, 2001; Petch *et al.*, 2002; Khairoutdinov and Randall, 2003). For example, Weisman *et al.* (1997) show that a 4-km horizontal grid spacing in a cloud resolving model is necessary to reproduce squall-line evolution and structure. Recent simulations with a cloud resolving model indicate a variation of hydrometeor mixing ratio and cloud fraction among simulations with grid resolutions coarser than 4 km, but no sensitivity for grids finer than 4-km spacing (Khairoutdinov and Randall, 2003). In simulations of four convective events with a mesoscale model, Bernardet *et al.* (2000) find that fine grid spacing of 2 km is needed to capture convection explicitly and to resolve low level jet (LLJ) strength, timing, and location. Simulations with the Penn State-NCAR Mesoscale Model MM5 of a midwestern US flood event suggest that a fine grid spacing of 1.67 km is necessary to capture intense precipitation (Roebber and Eise, 2001).

Even in high resolution model simulations, accurate initialization of a mesoscale model may be essential for accurate simulations of extreme precipitation. Small errors in the initial state can produce large errors later in the simulation. This sensitivity to initial conditions of numerical weather models is well established (Lorenz, 1963). Since many mesoscale models utilize initial states generated from global circulation models with a relatively coarse grid, essential mesoscale features may be excluded from the global initialization datasets. Recently, a 40-km reanalysis dataset from NCEP Eta Model has been made available for MM5 initialization. This high spatial resolution dataset offers a significant advance over the standard NCEP global reanalysis dataset with 2.5 degree resolution.

In addition, the temporal resolution of these datasets may have a strong impact on the simulation. Lateral boundary conditions pose a serious limitation on the accuracy of mesoscale models (Warner *et al.*, 1997). NCEP global reanalysis datasets are available only every 12 hours. These datasets are used to update the lateral boundary conditions. NCEP Eta reanalysis datasets are available every 3 hours, so lateral boundaries are supplied with higher resolution, more frequent large-scale forcing with Eta reanalysis.

Land-atmosphere interaction may play an important role in the development of clouds and subsequent precipitation (e.g., Avissar and Liu, 1996; Eltahir, 1998; Lynn *et al.*, 1998;

Pielke, 2001; Baker *et al.*, 2001). Thus, a sophisticated land surface model coupled to a mesoscale model may be essential for accurate prediction of many flood events. For example, a standard land surface scheme in MM5 uses a two layer force-restore method in which soil temperature evolves in response to radiative surface fluxes but soil moisture remains fixed throughout the simulation. Lynn *et al.* (2001) show that inclusion of a more sophisticated land surface treatment with two-way interaction of soil moisture produces more realistic simulations of Florida convection. Similarly, simulations of the Buffalo Creek 1996 flood event indicate that an advanced land surface model with time-varying soil moisture fields is necessary to produce heavy rainfall in the correct location (Chen *et al.*, 2001).

The purpose of this paper is to investigate the impact of model initialization and land surface treatment on the ability of a high-resolution mesoscale model to reproduce heavy rainfall of the 6-7 May 2000 Missouri flash flood event. The next section describes the 6-7 May 2000 flood event in more detail. Section 3 describes the mesoscale model used to produce the numerical simulations and outlines the numerical simulations. Results of the numerical simulations are shown in section 4, followed by a discussion of these results in the final section.

2. 6-7 May 2000 Missouri Flood

On 6-7 May 2000, thunderstorms produced heavy rainfall and historic flash flooding in east-central Missouri with over 340 mm of rain in some areas (Glass, 2001; Market *et al.*, 2001). The mesoscale convective system (MCS) responsible for this heavy precipitation developed from a mesoscale convective vortex (MCV) from a system that produced heavy rainfall and flash flooding in northeast Oklahoma the preceding day. At 0000 UTC 7 May, the MCV was located over central Missouri. Thunderstorms developed 1-2 hours later near the center of the vortex. By 0400 UTC, organization of these storms had increased due to interaction with the low level jet (LLJ). Development of new cells occurred at the intersection of the LLJ and cold outflow boundary on the southwestern boundary of the system. From 0600 to 1100 UTC, the MCS remained quasi-stationary over east-central Missouri with rain rates of 50-100 mm per hour in some locations. Around 1200 UTC, quasi-stationary motion ceased and the system moved eastward into Illinois. Further details of this storm are described in Glass (2001). The 6-7 May 2000 Missouri flood event has been used for Cooperative program for Operational Meteorology, Education and Training (COMET) courses at the Cooperative Institute for Precipitation Systems (CIPS) in St. Louis.

Figure 1 shows the 24-hour accumulated rainfall estimate from 1200 UTC 6 May 2000 to 1200 UTC 7 May 2000 by the St. Louis WSR-88D radar (KLSX). The heaviest rainfall occurred southwest of St. Louis in Franklin County, with radar estimates of over 260 mm in some locations. Glass (2001) reports that the KLSX radar underestimated precipitation for this event by 10-30%, and that the largest total rainfall measured by a rain gauge was 343 mm at Union, Missouri (38.2 N, 91.5 W).

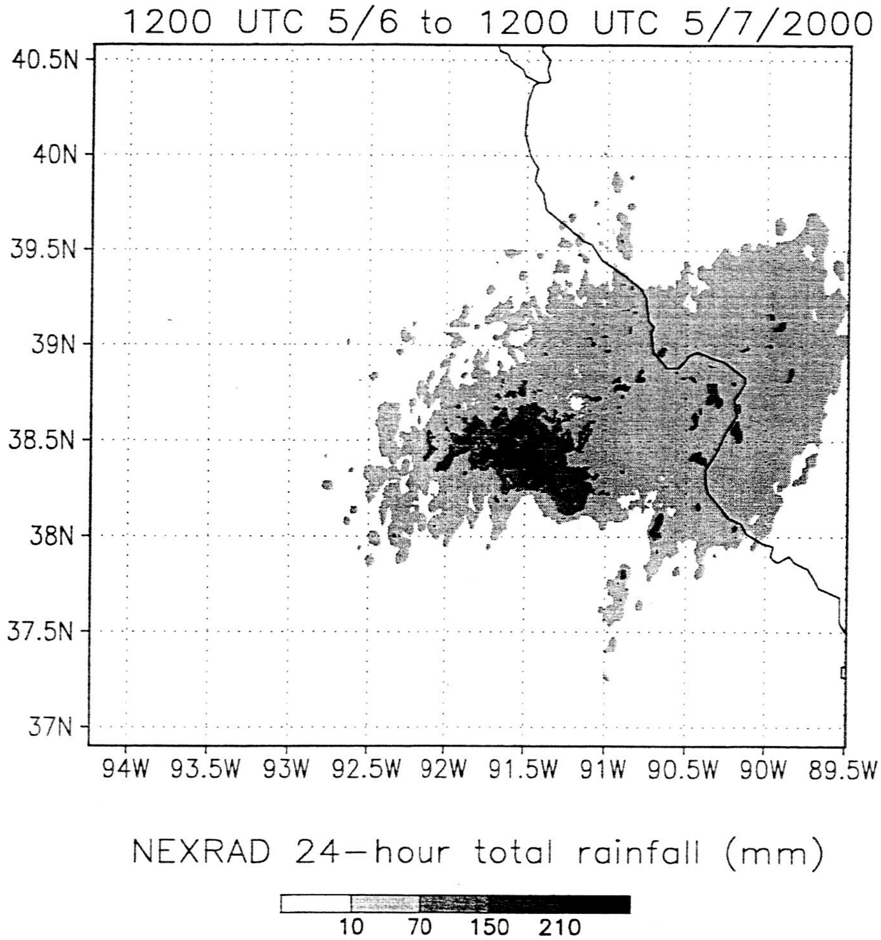

Figure 1: 24-hour total rainfall estimates from 1200 UTC 6 May 2000 to 1200 UTC 7 May 2000 by the KLSX WSR-88D radar in St. Louis, Missouri.

3. Model

In this study, we utilize a sophisticated atmosphere/land-surface numerical model (MM5-PLACE) to test the impact of model initialization and land-surface processes on simulation of heavy precipitation. The atmospheric component of the model is the Penn State-NCAR Mesoscale Model MM5 Version 2.7 (Duhdia, 1993). Two surface models are considered: 1) the SLAB model provided by MM5, and 2) the Goddard Parameterization for Land-Atmosphere-Cloud Exchange (PLACE; Wetzel and Boone, 1995). The SLAB model calculates the surface energy budget of a single soil layer using the force-restore method, but soil moisture remains fixed. By contrast, PLACE considers five soil moisture layers and seven soil temperature layers. Momentum, sensible, and latent heat fluxes are calculated using similarity relationships. Importantly, soil moisture varies throughout the simulation in the PLACE model, thus providing two-way moisture feedback between the land surface and the atmosphere. Further details on MM5-PLACE can be found in Lynn *et al.* (2001). MM5-PLACE has previously been used to investigate sea-breeze initiated convection in Florida (Lynn *et al.*, 2001), land cover influence on surface temperature in Oklahoma (Crawford *et al.*, 2001), and heavy rainfall events associated with the Mei-Yu front in China (Qian *et al.*, 2004).

Figure 2 shows three nested grids used for the MM5-PLACE simulations with grid spacings of 15 km, 5 km, and 1.67 km. Time steps on the three grids are 60, 20, and 6.7 s, respectively. The 15-km outer grid utilizes Kain-Fritsch cumulus parameterization, while the 5-km and 1.67-km grids use the Goddard explicit cloud microphysics scheme (Tao *et al.*,

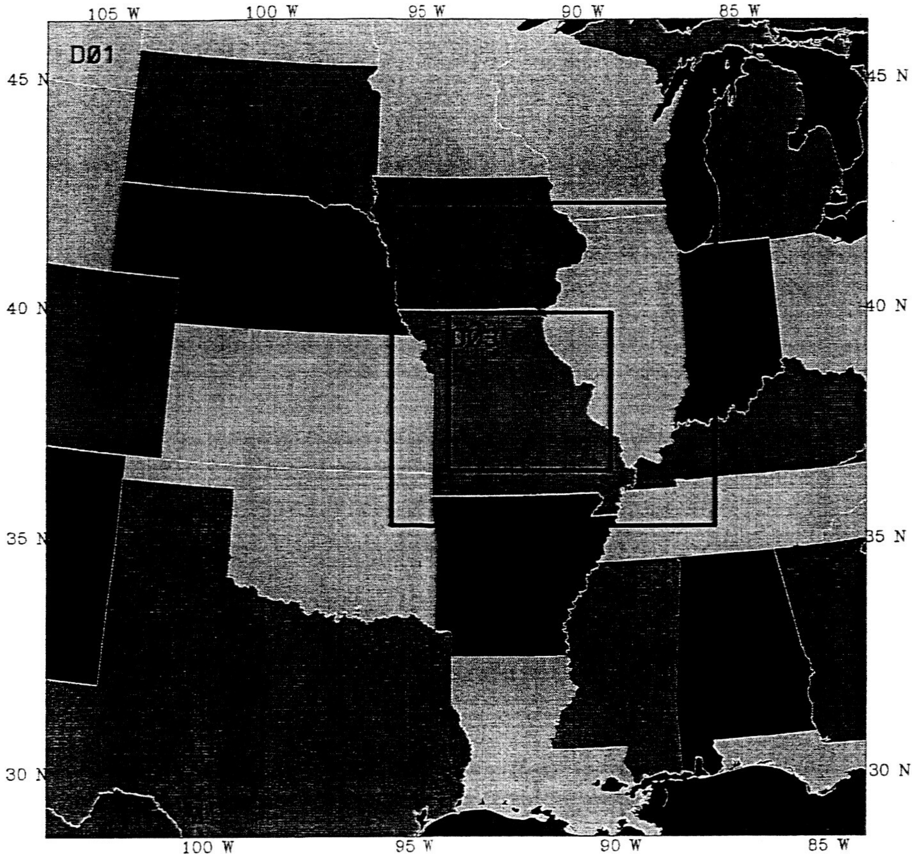

Figure 2: Nested grids used in the MM5 simulations.

2003). There are 23 terrain-following sigma layers in the vertical with the lowest layer roughly 40 m above the ground. The Blackadar planetary boundary layer scheme is implemented in all cases. Simulations are integrated for 24 hours from 1200 UTC 6 May 2000 to 1200 UTC 7 May 2000.

Four numerical experiments were performed to investigate the impact of model initialization and land surface treatment on simulation of the 6-7 May 2000 Missouri flash flood. Table I summarizes the simulations conducted in this study. Atmospheric initialization of

MM5-PLACE occurs by two different means. NCEP global reanalysis with 2.5-degree spatial resolution and 12-hour temporal resolution provides standard initial conditions and boundary conditions for MM5. Higher spatial (40-km grid spacing) and temporal (3 hour) resolutions for initial and boundary conditions are available for this flood event from Eta reanalysis datasets (Figure 3). The higher resolution Eta reanalysis initialization contains mesoscale features of the 6 May 2000 Oklahoma MCS that are likely important for initiating the Missouri MCS on the following day. At 850-mb height, Eta reanalysis at 1200 UTC 6 May 2000 indicates a strong east-west gradient in relative humidity over the central United States, while the NCEP global initialization shows weaker variation in relative humidity. At 500-mb height, Eta reanalysis shows a tight cyclonic circulation (the residual MCV associated with the Oklahoma MCS) centered over southeastern Kansas. With NCEP global initialization, a weaker cyclonic circulation is centered over north-central Kansas. Two simulations (Cases A and B) utilize NCEP global reanalysis initial and boundary conditions, and two simulations (Cases C and D) use Eta reanalysis high-resolution initialization and boundary conditions.

To test the effect of land surface treatment, two simulations (Cases A and C) use the simple SLAB model while two simulations (Cases B and D) implement the more realistic PLACE land surface model. Default land use categories from MM5 are used in all cases. The PLACE model requires additional land surface parameters not supplied by MM5. In the PLACE simulations, vegetation types are directly related to standard MM5 land types. Additional surface characteristics such as soil type, fractional vegetation cover, leaf area index, albedo, and surface roughness are provided from the International Satellite Land Sur-

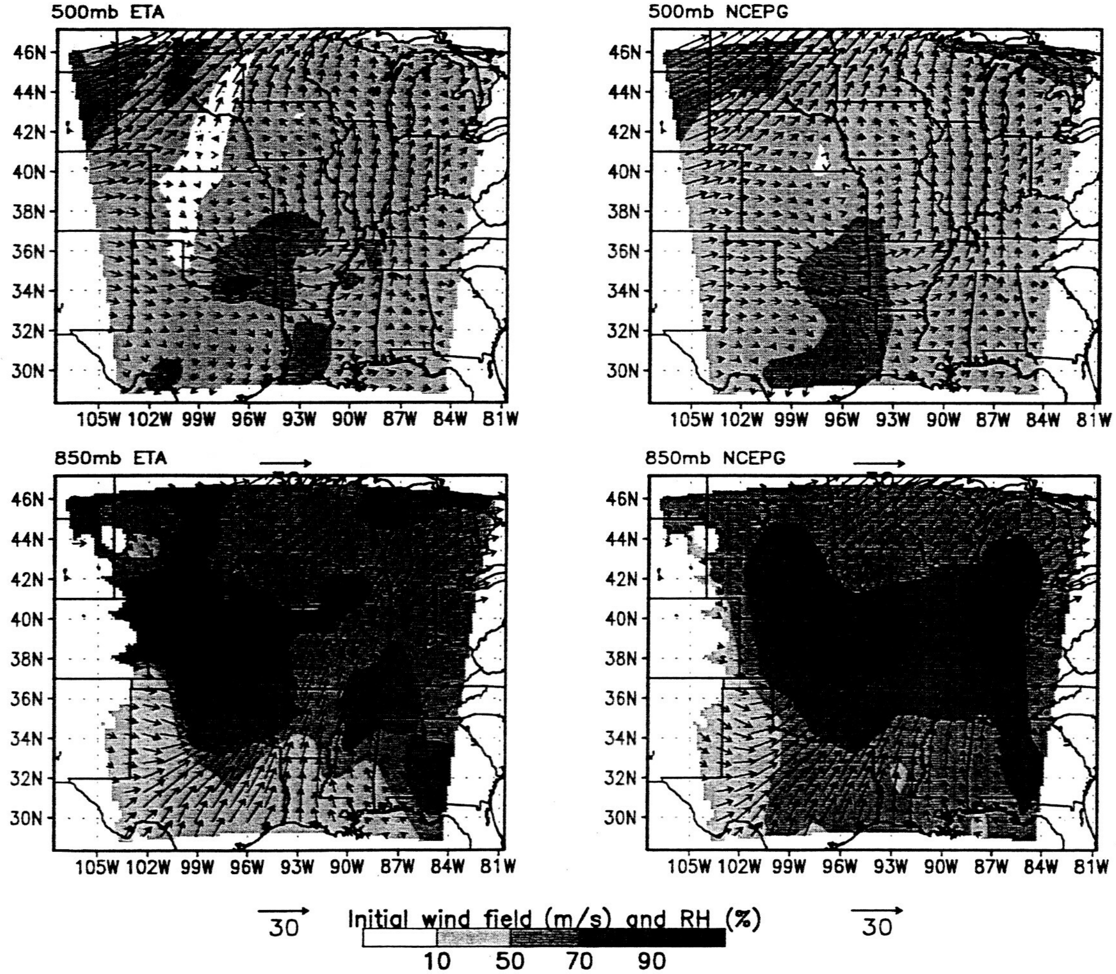

Figure 3: Initial relative humidity and horizontal winds on 1200 UTC 6 May 2000 at 500-mb and 850-mb heights provided by NCEP Eta reanalysis (left column) and NCEP global reanalysis (right column).

Table I: Model simulations.

Case	Initialization	Land Surface Model
A	NCEP global 2.5-deg, 12-hr	SLAB
B	NCEP global 2.5-deg, 12-hr	PLACE
C	Eta 40-km, 3-hr	SLAB
D	Eta 40-km, 3-hr	PLACE

face Climatology Project (ISLSCP; Meeson *et al.*, 1995). Soil moisture and soil temperature initial conditions from MM5-supplied climatological data are used in all simulations.

4. Results

Figure 4 shows the 24-hour accumulated rainfall from 1200 UTC 6 May to 1200 UTC 7 May for the four simulations. Care should be taken when comparing simulated rainfall with radar-estimated rainfall (Figure 1). First, radar underestimates rainfall amounts by 10-30% when compared to rain gauge measurements for this event (Glass, 2001). Second, the range of the St. Louis KLSX radar does not cover the entire inner domain. Thus, areas at a distance of over 2 degrees from KLSX (38.7 N, 90.7 W) with no measured rainfall are outside the effective range of the radar. Rainfall likely occurred in these regions. Third, simulated rainfall near the boundaries may be the result of spurious gradients imposed by two-way interactive grid nesting and may not be physical.

With these caveats, the simulation with high resolution Eta reanalysis initialization and

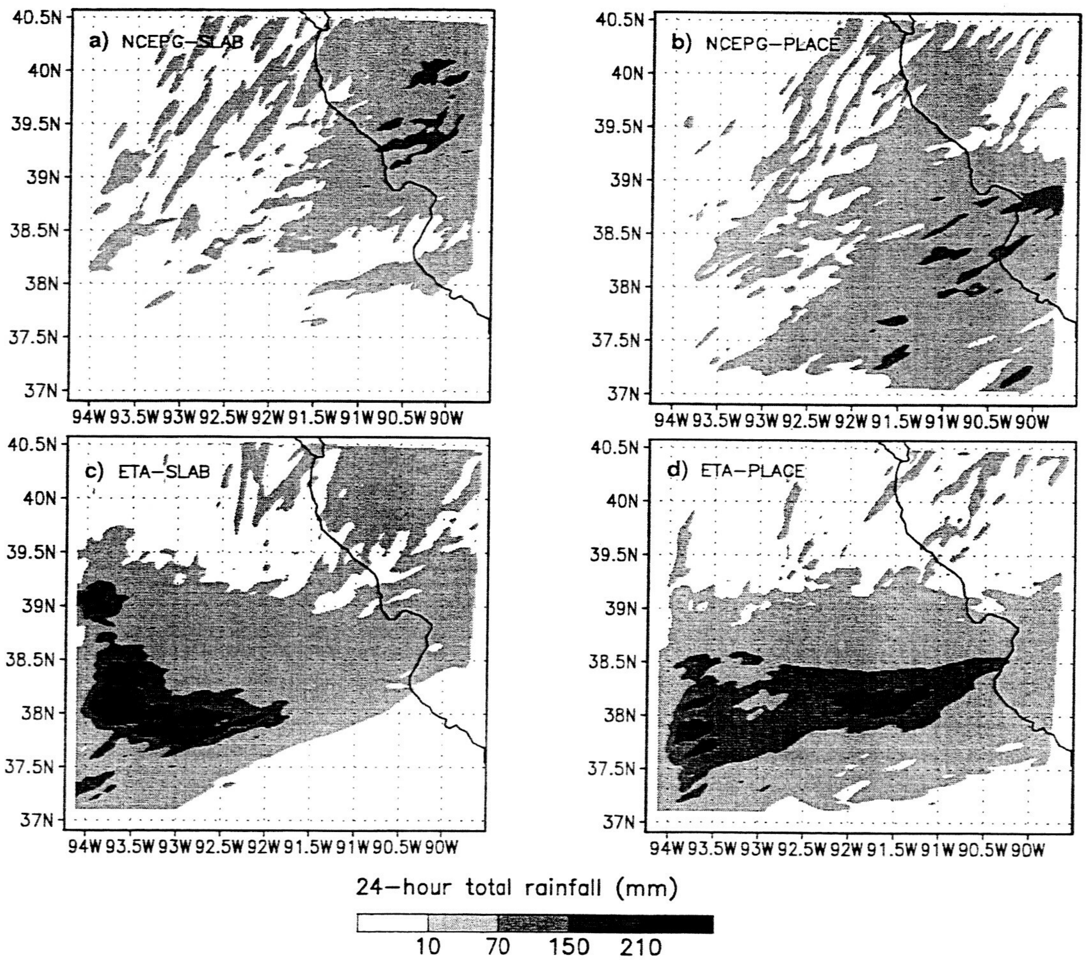

Figure 4: 24-hour accumulated rainfall from 1200 UTC 6 May 2000 to 1200 UTC 7 May 2000 for four simulations with different initializations and different land surface treatments: a) NCEP global reanalysis initialization and SLAB land model, b) NCEP global reanalysis initialization and PLACE land model, c) Eta reanalysis initialization and SLAB land model, and d) Eta reanalysis initialization and PLACE land model.

with the PLACE land surface model (Case D) best reproduces observed total rainfall. Simulations with coarse NCEP global reanalysis initialization (Cases A and B) severely underestimate total rainfall, while simulations with high-resolution Eta reanalysis initialization (Cases C and D) produce significantly higher total rainfall amounts. Improved simulations with Eta reanalysis initialization are likely caused by improved detail of the residual MCV over Kansas and Oklahoma at 1200 UTC 6 May (Figure 3) which helped initiate the 7 May Missouri MCS. Furthermore, the land surface treatment has a major impact on the location of precipitation. Simulations with a simple SLAB land surface (Cases A and C) miss the location of heaviest rainfall by over 150 km, while simulations with the more realistic PLACE land surface (Cases B and D) produce the heaviest rainfall within 50 km of the observed location.

Figure 5 shows the time series of accumulated rainfall for the four simulations near the Union rain gauge site that recorded the largest rainfall amounts for this event. To minimize the effect of the heaviest rainfall being located only a few grid points from the Union site, rainfall amounts in Figure 5 for the four simulations are calculated by taking the average rainfall over a 20 km^2 area. Two key results can be seen in this plot. First, all simulations underestimate the total accumulated rainfall observed at Union (343 mm). However, the simulation with high resolution initialization *and* a sophisticated land surface scheme (Case D, Eta-PLACE) produces the heaviest rainfall at this location, with over 156 mm of precipitation. (The maximum accumulated rainfall amount in Case D (over 210 mm) occurs just east of the Union site). The next best simulation (Case C, Eta-SLAB) produces only 38 mm of precipitation near the Union site. Second, simulated precipitation at the Union location occurs earlier and ends earlier than observed precipitation. For example, rainfall in the Eta-PLACE simulation (Case D) begins 3 hours earlier than rainfall detected by the Union rain gauge. The Eta-PLACE simulation produces rainfall at this site for roughly 6 hours, while observed precipitation lasted for 9 hours. These results suggest that the MCS propagated more rapidly in the simulations than observed. The large amount of observed rainfall occurred because the MCS moved slowly and then stalled over east-central Missouri, a process only partially reproduced in the simulations.

Improvement in the location of heavy precipitation in PLACE simulations can be attributed to a change in the strength and location of the LLJ. Figure 6 shows a cross section at 37.5 N latitude of southerly winds at 0600 UTC 7 May in the lower atmosphere for Cases C and D. The case with the PLACE land surface model shows a larger region with winds over 20 m s^{-1} than the case with the simple SLAB land surface. In addition, the region of maximum winds occurs further eastward in the PLACE simulation. The position of the LLJ in the PLACE simulation is consistent with LLJ location at 0600 UTC from RUC analysis (Glass, 2001). Since development of new convection happens at the intersection the LLJ and the southwestern cold outflow boundary, low-level jet location helps determine the area of heavy precipitation. The heaviest rainfall in the PLACE simulation occurs at roughly 91.5 W longitude, in agreement both with LLJ location and with the observed location of heavy precipitation.

In these simulations, the land surface influences the LLJ through partitioning of sensible

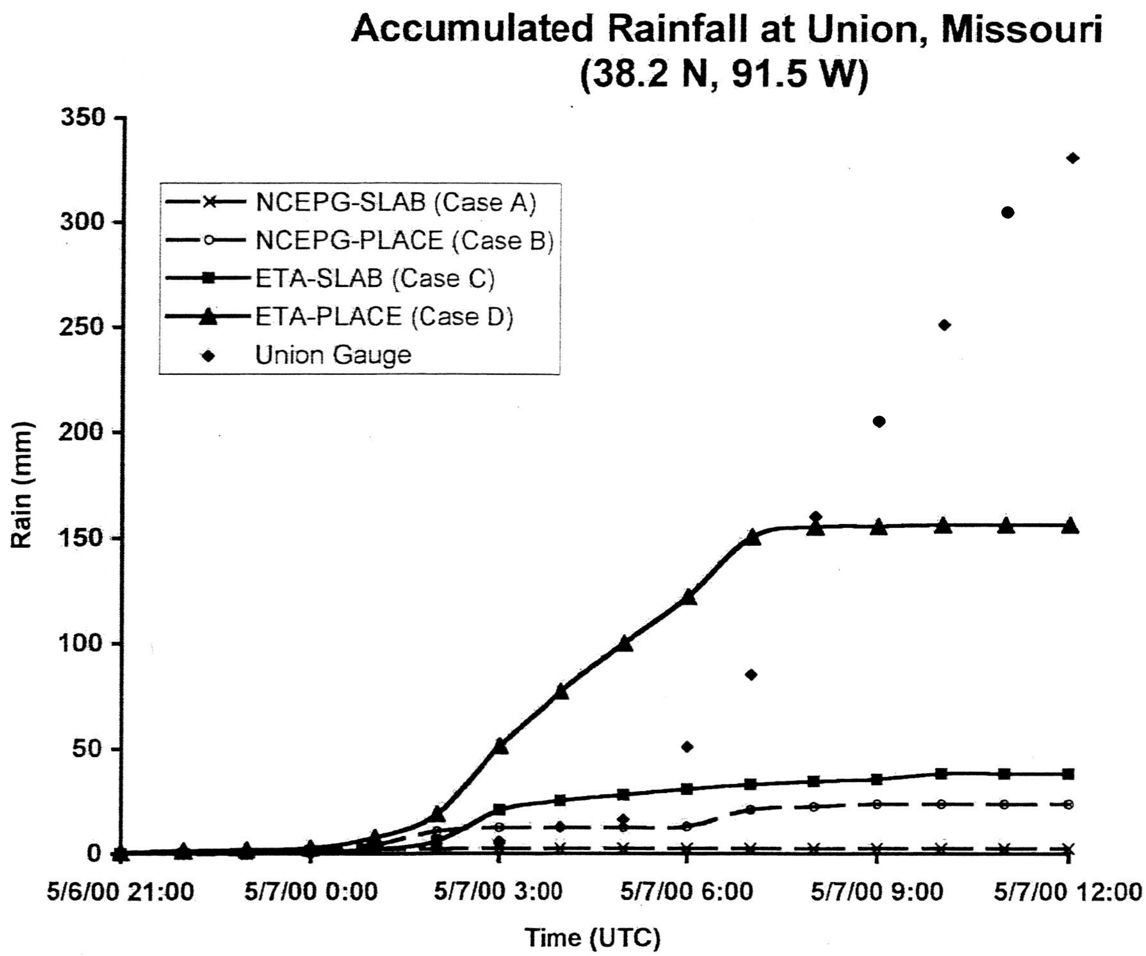

Figure 5: Time series of accumulated rainfall from 2100 UTC 6 May 2000 to 1200 UTC 7 May 2000 at Union, Missouri, for four simulations with different initializations and different land surface treatments. Observed rainfall measurements from Glass (2001) from the Union Station rain gauge are also plotted.

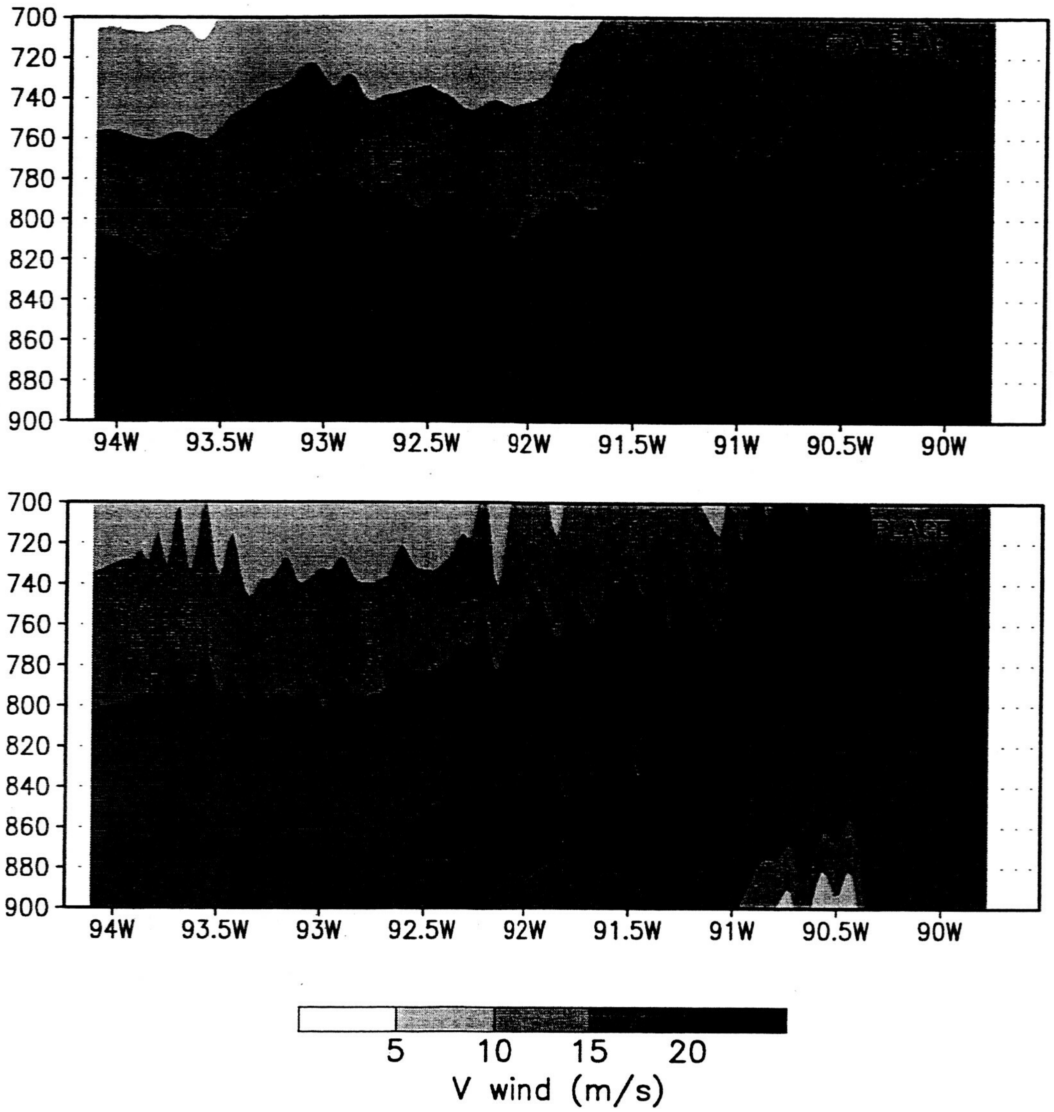

Figure 6: Cross section of southerly winds at 37.5 N latitude at 0600 UTC 7 May 2000 for Case C (Eta-SLAB; upper panel) and Case D (Eta-PLACE; lower panel).

and latent heat fluxes. One key mechanism of LLJ formation involves horizontal differences in heat fluxes which can produce strong, shallow baroclinicity in the boundary layer (Stensrud, 1996). For example, soil moisture gradients, which in turn produce gradients in sensible heat and latent heat fluxes, have been shown to enhance LLJ formation in many heavy precipitation events (e.g., Paegle *et al.*, 1996; Bosilovich and Sun, 1999; Bernardet *et al.*, 2000). Figure 7 shows sensible heat fluxes at 0600 UTC 7 May 2000 for Cases C and D. The simulation with the PLACE land model (Case D) shows a signficantly stronger gradient in sensible heat flux throughout east-central Missouri. Over an west-to-east horizontal span of roughly 50 km, sensible heat fluxes vary by over 150 W m^{-2}. This strong gradient in sensible heat produces a horizontal temperature gradient in the boundary layer, thereby enhancing a low-level jet near the top of the boundary layer.

Two-way interaction between the land surface and the atmosphere also produces greater spatial variability in latent heat fluxes. Figure 8 shows latent heat fluxes at 0600 UTC 7 May 2000 for Cases C and D. The general distribution of latent heat flux is similar between the two cases, with larger values of latent heat flux in the southern and eastern portions of the domain. However, Case D with the PLACE land model exhibits small-scale spatial variability with latent heat fluxes ranging from values less than 20 W m^{-2} to values over 150 W m^{-2} in a horizontal span of less than 50 km. Indeed, variability in latent heat flux can be found from grid cell to grid cell. This small-scale structure likely results from rainfall-soil moisture feedback and statistical sub-grid soil variability in the PLACE model (Boone and Wetzel, 1999).

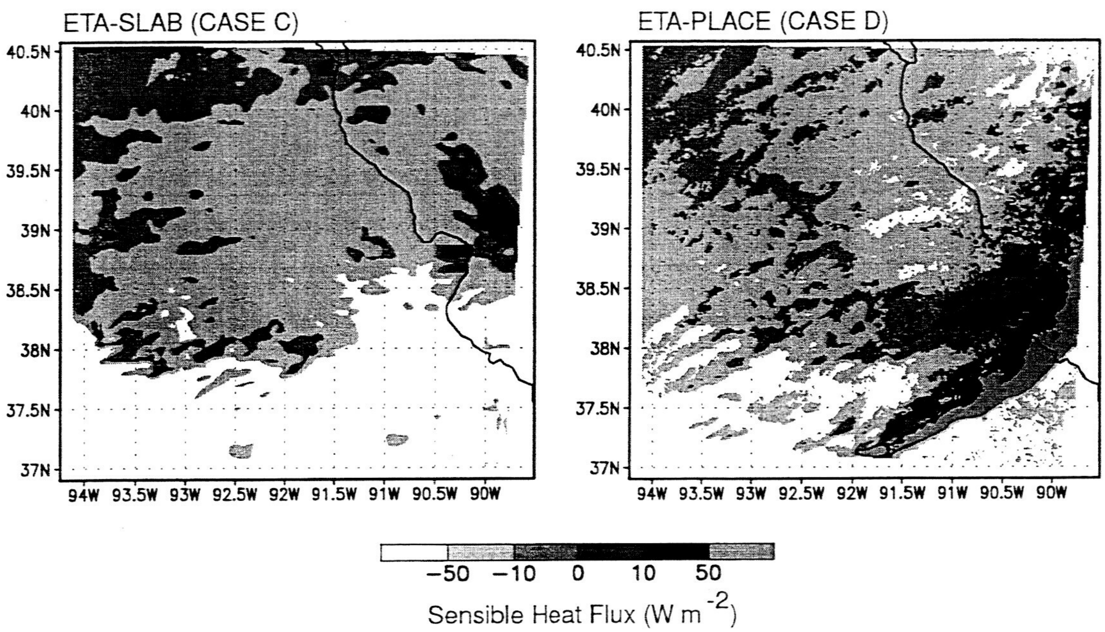

Figure 7: Sensible heat fluxes at 0600 UTC 7 May 2000 for Case C (Eta-SLAB) and Case D (Eta-PLACE).

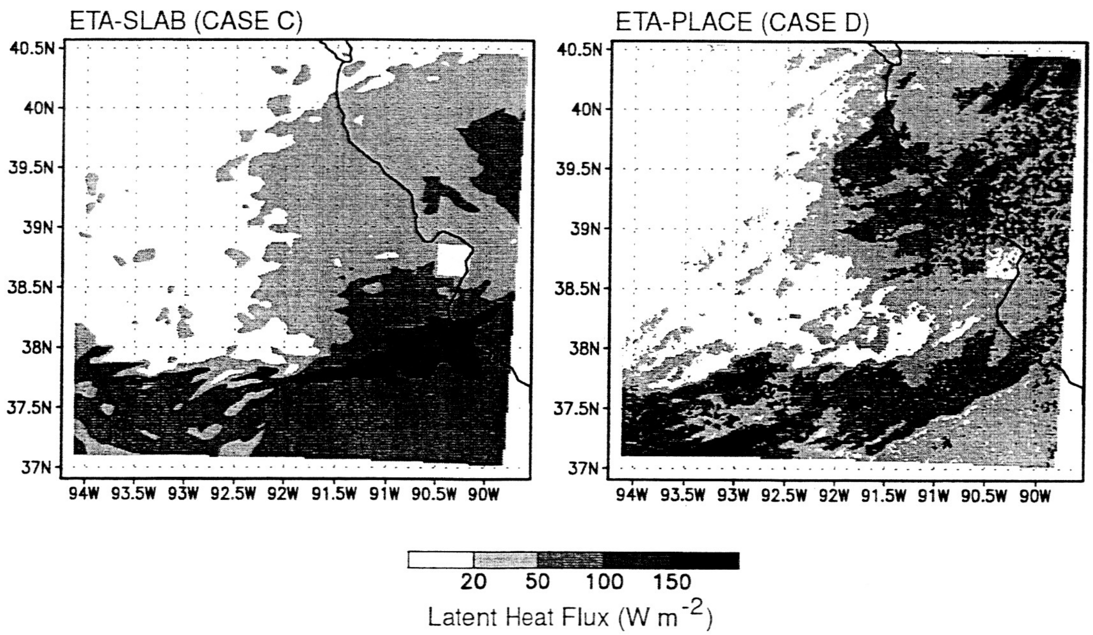

Figure 8: Latent heat fluxes at 0600 UTC 7 May 2000 for Case C (Eta-SLAB) and Case D (Eta-PLACE).

5. Discussion

High-resolution mesoscale model simulations were performed of the 6-7 May 2000 flash flood event in east-central Missouri to examine the impact of model initialization and land surface treatment on timing, intensity, and location of extreme precipitation. Two different types of model initialization were employed: 1) NCEP global reanalysis with 2.5-degree grid spacing and 12-hour temporal resolution, and 2) Eta reanalysis with 40-km grid spacing and 3-hour temporal resolution. In addition, two different land surface treatments were considered. A simple land scheme (SLAB) keeps soil moisture fixed at initial values throughout the simulation, while the more sophisticated PLACE land model allows for rainfall-soil moisture interactive feedback.

Simulations with high resolution model initialization show considerable improvement in the intensity of precipitation. Eta reanalysis initialization with 40-km grid spacing captures the residual MCV from a mesoscale convective system over Oklahoma on 5-6 May 2000. The MCV helps organize convection and aids in the development of the 6-7 May 2000 convective system. In contrast, coarse resolution NCEP global initialization shows a weak cyclonic circulation at 500 mb height but not the detailed structure of an MCV. Accordingly, MCS development is much weaker with NCEP global initialization. While simulations with Eta reanalysis initialization exhibit over 200 mm of accumulated rainfall in some areas, simulations with NCEP global initialization produce maximum rainfall less than half of this amount.

The PLACE land surface model leads to improved location of heavy precipitation over the simple SLAB model. Since soil moisture can vary over time in response to precipitation in the PLACE model, the partition of energy into sensible and latent heat fluxes is more realistic. Strong spatial gradients in sensible heat and latent heat fluxes are found in simulations with the PLACE model. The planetary boundary layer then develops more realistically as sensible and latent heat fluxes evolve both spatially and temporally. At the top of the boundary layer, a low-level jet develops in response to strong gradients in sensible heat flux. The simulation with the PLACE model and high resolution Eta reanalysis initialization best reproduces the location of the LLJ for the 6-7 May 2000 event. The LLJ then interacts with the cold outflow boundary of the MCS to initiate new convective cells. These cells produce heavy precipitation near the location of peak observed rainfall.

Quasi-stationary motion of the 6-7 May 2000 mesoscale convective system contributed to heavy rainfall amounts near Union, Missouri. The Union rain gauge recorded precipitation for 9 hours with an average rain rate of 38 mm/hr. The Eta-PLACE simulation produces a relatively large average rain rate of 26 mm/hr, but rainfall lasts for less than 6 hours at the Union location. Obviously, the simulated MCS moves more rapidly and therefore dumps less rainfall than the observed system. One possible cause for faster storm motion of the simulated MCS involves the relatively small domain size of the inner grid. The inner grid with 1.67-km grid spacing covers a relatively small region in east-central Missouri and western Illinois. Although infrared satellite imagery (not shown) indicates that the coldest cloud tops remain within the area covered by the inner domain, the areal coverage of the developing MCS extends well beyond that of the inner grid into northern Arkansas, western

Tennessee, and western Kentucky. Thus, lateral boundaries for the inner grid (and even perhaps for the middle grid with 5-km grid spacing) are located too closely to the storm location, thereby introducing errors in storm development and propagation. Unfortunately, lateral boundaries had to be located this closely given the need for high-resolution simulations and computational limitations.

Given the strong impact the land surface has on the intensity and location of heavy precipitation, the distribution of initial soil moisture may influence storm development. In these simulations, climatological values of soil moisture from the MM5 dataset were used. This soil moisture distribution does not accurately reflect specific soil conditions on 6 May 2000. For example, soil moisture estimates from Eta reanalysis on 6 May 2000 show a strong southeast-northwest gradient in soil moisture over the central United States, while MM5 climatology shows little spatial variation in soil moisture. These soil moisture gradients may further enhance development of the LLJ. Future simulations should investigate the impact of more realistic values of soil moisture (provided by Eta reanalysis or by satellites such as NASA's Terra satellite) on MCS development.

Accurate simulation of MCS precipitation events is essential for effective public warning of flash flooding. Weather forecasts on 6 May predicted roughly 0.5 inches of rain from this system. In actuality, this storm dumped over 13 inches of rain in some areas in 9 hours. The simulations conducted here with high resolution initial conditions produce heavy rainfall with over 8 inches of rain in some areas. The use of a sophisticated land surface model with time-varying soil moisture further improves the location of heavy precipitation. Even though the peak amounts of precipitation are underestimated in these models, the presence of heavy rainfall in the correct location marks a significant improvement in numerical weather prediction capabilities. These results suggest that numerical weather prediction models used for public warning of MCS-related flash flood events could benefit tremendously from the use of high resolution initialization and two-way interactive land-atmosphere schemes. Still, additional work on numerous flash flood case studies is required to ascertain the general effect of model initialization and land surface treatments on simulation of extreme precipitation events.

Acknowledgments.

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High-resolution mesoscale simulations of the 6-7 May 2000 Missouri flash flood: Impact of model initialization and land surface treatment.

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Popular Summary

High-resolution mesoscale model simulations of the 6-7 May 2000 Missouri flash flood event were performed to test the impact of model initialization and land surface treatment on timing, intensity, and location of extreme precipitation. In this flash flood event, a mesoscale convective system (MCS) produced over 340 mm of rain in roughly 9 hours in some locations. Two different types of model initialization were employed: 1) NCEP global reanalysis with 2.5-degree grid spacing and 12-hour temporal resolution, and 2) Eta reanalysis with 40-km grid spacing and 3-hour temporal resolution. In addition, two different land surface treatments were considered. A simple land scheme (SLAB) keeps soil moisture fixed at initial values throughout the simulation, while a more sophisticated land model (PLACE) allows for rainfall-soil moisture interactive feedback.

Simulations with high-resolution Eta model initialization show considerable improvement in the intensity of precipitation due to the presence in the initialization of a residual mesoscale convective vortex (MCV) from a previous MCS. Simulations with the PLACE land model show improved location of heavy precipitation. Since soil moisture can vary over time in the PLACE model, surface energy fluxes exhibit strong spatial gradients. These surface energy flux gradients help produce a strong low-level jet (LLJ) in the correct location. The LLJ then interacts with the cold outflow boundary of the MCS to produce new convective cells. The simulation with both high-resolution model initialization and time-varying soil moisture best reproduces the intensity and location of observed rainfall.